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IMPORTANCE OF AGGREGATION AND SMALL ICE CRYSTALS IN CIRRUS CLOUDS,
BASED ON OBSERVATIONS AND AN ICE PARTICLE GROWTH MODEL

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The 1 November 1986 FIRE I case study was used to test an ice particle growth model which predicts bimodal size spectra in cirrus clouds. The model was developed from an analytically based model which predicts the height evolution of monomodal ice particle size spectra from the measured ice water content (IWC). Size spectra from the monomodal model are represented by a gamma distribution,

$$N(D) = N_0 D^\nu \exp(-\lambda D), \quad (1)$$

where D = ice particle maximum dimension. The slope parameter, λ , and the parameter N_0 are predicted from the IWC through the growth processes of vapor diffusion and aggregation. The model formulation is analytical, is computationally efficient, and well suited for incorporation into larger models. The monomodal model has been validated against two other cirrus cloud case studies as described in Mitchell (1993; 1991). From the monomodal size spectra, the size distributions which determine concentrations of ice particles $< 150 \mu\text{m}$ are predicted.

Ice particle size spectra measured by the DRI ice particle replicator on 21 Nov. 1991 during FIRE II indicate ice particles in cirrus with $10 \mu\text{m} < D < 150 \mu\text{m}$ conform to an exponential size distribution with approximately constant slope. Based on 21 size distributions, $\lambda = 226 \pm 35 \text{ cm}^{-1}$. Size spectra from the 2D-C probe for 1 Nov. 1986 (during FIRE I) exhibited a similar constant slope value (about 250 cm^{-1}) for $50 \mu\text{m} < D < 150 \mu\text{m}$. Assuming this result is general for most cirrus, this enables the component of the size distribution containing particles $< 150 \mu\text{m}$ to be predicted from the size distribution containing larger particles, which is predicted by the growth processes of vapor diffusion and aggregation.

The height evolution of ice particle size spectra was measured during a Lagrangian spiral descent through a relatively uniform cirrus deck during FIRE I on 1 Nov. 1986. Cloud depth ranged from 9 km to about 5.1 km. Model predicted and measured size distributions were plotted and compared favorably, as shown in Fig. 1a-1b. Measured size distributions are indicated by the solid lines, and size spectra predicted by the ice particle growth model are indicated by the long dashed lines. The short-dashed lines are predicted for vapor deposition growth only (no aggregation). These spectra would occur if ice crystals did not combine to form aggregates, and remained as single ice crystals. The model assumes all ice particles are single ice crystals at cloud top (no aggregation), and thus there is no difference between the two predicted spectra at cloud top. The lower the level in the cloud, the more time there is for aggregation to occur as ice falls from cloud top, and the size spectra broaden to include the larger aggregates.

Since no theoretical method for predicting ν is known, ν was given a constant value of 5. This parameter controls the degree of bimodality (i.e. the magnitude of the secondary maximum) in the size distribution. The parameter ν varied between 3 at cloud base to 16 at cloud top. Since ν is underestimated in the model in the upper cloud, the observed bimodality is underestimated by the model predicted spectra above 7.4 km. Overall, however, the model predicted size spectra agree fairly well with the observed size spectra, especially at the smaller sizes. Since crystals $< 150 \mu\text{m}$ may contribute significantly to size distribution area, the model appears well suited for predicting cirrus cloud radiative properties.

The ice water content was fairly constant throughout most of the cloud, indicating vapor deposition or sublimation did little to change ice particle sizes. This was confirmed by the model. The updraft calculated from the IWC was $\leq 10 \text{ cm s}^{-1}$, and should not significantly

affect ice particle size based on model results. Advection should not affect ice particle sizes since the sampling was conducted in a Lagrangian spiral descent. This leaves aggregation as the process most likely to account for the observed increase in ice particle size. These conditions made it possible to determine the mean cloud aggregation efficiency from the model and the field data. The mean aggregation efficiency was about 0.5 ± 0.1 (depending slightly on what ice crystal mass-dimension relationship is used), which is typical of values calculated for frontal clouds. Ice particles descending over 3 km increased in mean size due to aggregation by about 40%.

Clear evidence of highly aggregated precipitation in cirrus was observed on replicator images of ice particles obtained during FIRE II on 5 Dec. 1991. Most particles $> 100 \mu\text{m}$ were aggregates comprised of side planes and columns, as shown in Fig. 2. Side planes were always abundant in aggregates. Recent observations of single columns, bullets, and bullet rosettes in cirrus clouds by Matsuo et al. (1993) show no evidence of aggregation for these crystal types. Thus it is postulated that side planes are required for significant aggregation in cirrus clouds. They appear to act as the "glue" which bind other crystals like columns to an aggregate. Both side planes and bullet rosettes are spatial crystal habits believed to form from freezing haze or cloud droplets. Side planes can grow effectively at just above ice saturation, while comparable growth rates for bullet rosettes require higher supersaturations (Furukawa 1982).

Aggregation reduced the optical depth of the 1 Nov. 1986 cirrus cloud by about 20%, relative to the optical depth predicted for growth by vapor diffusion only. This is illustrated in Fig. 3, where the solid line gives the extinction coefficient for size spectra predicted by vapor diffusion and aggregation, while the dashed line is for diffusion growth only. Aggregation reduces the total surface area of a size distribution by combining many small crystals into fewer ice particles, thus reducing the extinction coefficient. Consequently, the single scatter albedo, ω_0 , was significantly reduced in the near IR by aggregation growth. This is illustrated in Fig. 4, where ω_0 is predicted with (solid line) and without (dashed line) aggregation at a wavelength of $2.2 \mu\text{m}$. Calculations of the extinction and absorption coefficients were based on anomalous diffraction theory and the types of ice crystal habits observed by the 2D-C (spatial habits and columns), using the method described in Mitchell and Arnott (1993). The constant slope of the small particle end of the size distribution was used to extrapolate to zero size for these calculations.

Aggregation should also affect the phase function. As light passes through an ice crystal aggregate, multiple pairs of refraction events are likely and more side and back scattering should occur. Thus, the asymmetry factor might be lower in cirrus containing side planes if they are precursors for aggregation.

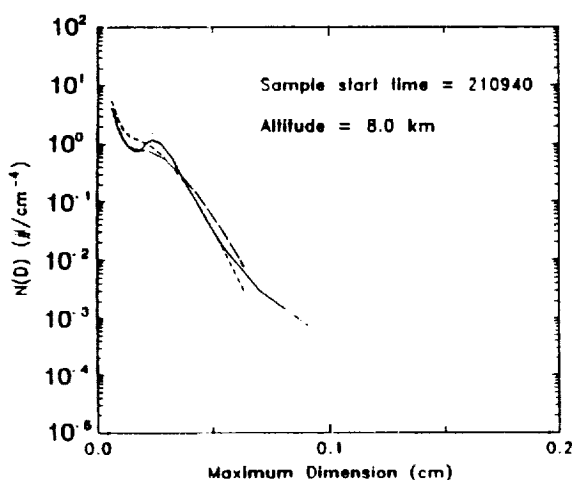


Fig. 1a. Comparison of size spectra from 1 Nov. case study (solid line) with model predicted spectra (long dashed line) and with spectra predicted without aggregation (short dashed line).

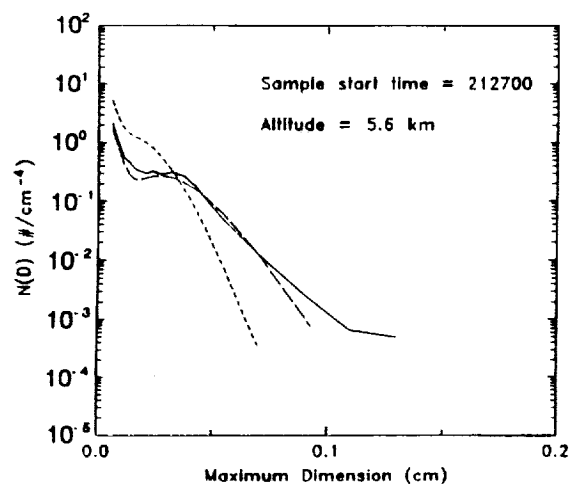


Fig. 1b. Same as Fig. 1 but at 5.6 km.



Fig. 2. A side plane/column aggregate from 5 Dec. 1991. Temperature was -40°C .

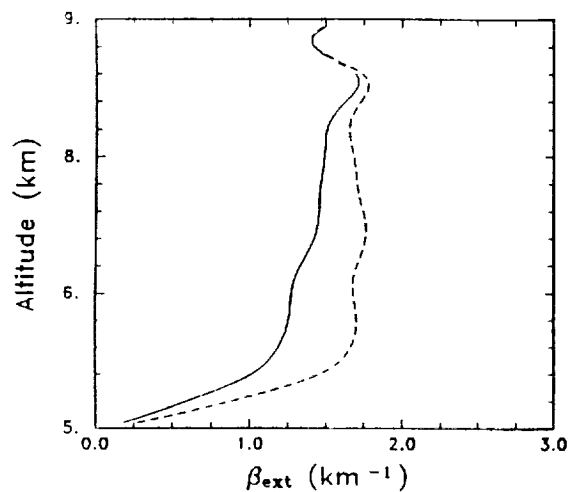


Fig. 3. Profile of the extinction coefficient for the 1 Nov. case study, predicted with (solid line) and without (dashed line) aggregation.

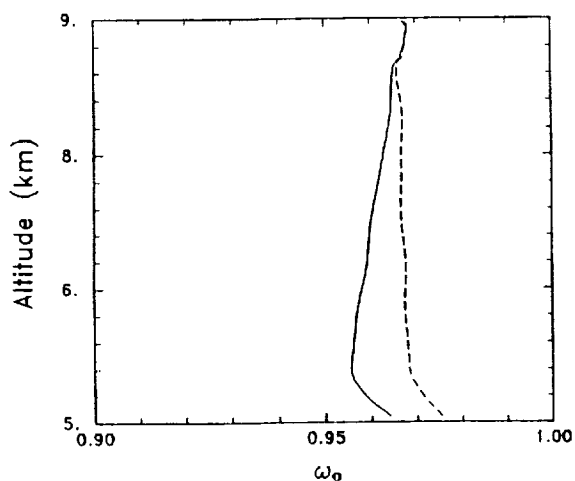


Fig. 4. Same as Fig. 3 except for the single scatter albedo.

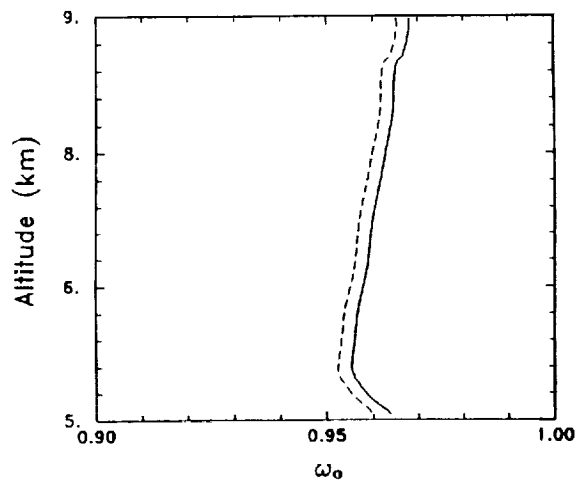


Fig. 5. Profile of the single scatter albedo calculated for all ice particles sizes (solid line), and for sizes $> 150 \mu\text{m}$ (dashed line).

In light of all this, a few comments about anvil cirrus in the equatorial Pacific are in order. The vast majority of ice crystals measured by the DRI replicator during TOGA COARE were side planes. Sizes were small, concentrations were high and they generally appeared aggregated (although the slow speed of the replicator film may have resulted in "piling up" of ice crystals). Similar observations were reported in Takahashi and Kuhara (1993) for tropical cirrus in the western Pacific. Spatial or polycrystalline ice crystals form from frozen cloud or haze droplets, where bullet rosettes are favored at higher supersaturations and side planes dominate at lower supersaturations (Furukawa 1982). If the lower stratosphere contains higher CCN concentrations, such as H_2SO_4 aerosol, than the upper troposphere, then anvil cirrus subjected to stratospheric mixing may receive higher CCN fluxes than other types of cirrus. Homogeneous freezing nucleation rates (Sassen and Dodd 1988) may thus be relatively high, decreasing supersaturations and promoting side planes. The high area to mass ratio for side planes (which increases single scatter albedo (Mitchell and Arnott 1993)), a relatively low asymmetry parameter, and the relatively small sizes and high concentrations of side planes may conspire to produce cirrus which are more reflective in the tropics than in other regions where stratospheric air is not involved. This reasoning supports the theory of Ramanathan and Collins (1992), which emphasizes the high albedo observed from tropical cirrus. It may also help explain the FIRE II observations of 5 Dec. 1991, where cirrus evidently formed in the Mt. Pinatubo aerosol plume (Sassen 1992). The anomalously high CCN concentrations may have depressed supersaturations, explaining the dominance of side planes on that day. On the other hand, aggregation will act to diminish cirrus albedo. As the IWC increases and cirrus thicken, aggregation growth (which depends on IWC) accelerates. All of these factors should be considered when evaluating the albedo and greenhouse effect of tropical cirrus clouds.

Predicted ice particles larger than about $150\text{ }\mu\text{m}$ accounted for 89% of the optical depth in the 1 Nov. 1986 case study. The predicted influence of ice crystals $< 150\text{ }\mu\text{m}$ on the single scatter albedo was weaker than the effect of aggregation, as shown in Fig. 5. This case study suggests that the discrepancy between reflectances predicted by radiative transfer models and measured reflectances is not due to extremely high concentrations of undetected ice crystals $< 50\text{ }\mu\text{m}$ in length.

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